

Optimization of Demand Hotspot Capacities using Switched Multi-Element Antenna Equipped Small Cells

Hamed Ahmadi*, Danny Finn*, Rouzbeh Razavi†, Holger Claussen†, Luiz A. DaSilva*

*CTVR Telecommunications Research Center, Trinity College Dublin, Ireland

†Bell Laboratories, Alcatel-Lucent, Ireland

Email: ahmadih,finnda,dasilval@tcd.ie, rouzbeh.razavi,holger.claussen@alcatel-lucent.com

Abstract—This paper presents switched Multi-Element Antennas (MEAs) as a simple, yet effective, method of enhancing the performance of small cell heterogeneous networks and compensating for the small cell base station sub-optimal placement. The switched MEA system is a low-cost system which enables the small cell to dynamically direct its transmission power toward locations of high user density, in other words *demand hotspots*. Our simulation results show that small cell base stations equipped with switched MEA systems offer greater performance than base stations equipped with omni-directional antennas in terms of both the number of users that can be served (and hence offloaded from the macrocell network) and in terms of overall network capacity. We also compare the performance of the switched MEA with fixed directional antennas and show that fixed-directional antennas can only outperform the switched MEA if the misalignment between their direction of transmission and the direction to the demand hotspot is less than 22.5° .

Index Terms—Antenna selection, Multi-element Antennas, Small cells

I. INTRODUCTION

Video streaming, online gaming and other data hungry applications cause high data consumption by mobile users. To deliver the required data rates and to satisfy the requested Quality of Service (QoS) mobile operators are developing small cells close to demand hotspots [1]. A *demand hotspot* is a location where a large number of network users are gathered. Bus or tram stops, shopping streets, and off-street food markets are examples of possible demand hotspots. Deploying Small Cell Base Stations (SCBSs) at these hotspots poses two main challenges: firstly, caused by requirements of the SCBSs, and secondly, due to the dynamic nature of demand hotspots.

An SCBS needs backhaul and power supply connectivity, neither of which will be available at all desired deployment locations, especially as network densities increase. Although using solar powered energy efficient SCBSs can solve the energy problem to some extent, providing reliable backhaul is still a challenge. There are also challenges

in site acquisition (even as small as a lamp post), in addition to energy and backhaul challenges. As a result, the SCBS will be deployed at the nearest location that satisfies all these conditions. Ideally the SCBS should be placed at the center of the demand hotspot but due to the aforementioned challenges it is likely that the SCBS is deployed in a place that is not the center of the demand hotspot or it might not even be inside the demand hotspot. This sub-optimal placement of the SCBS can significantly degrade the improvement that we expect by deploying an SCBS.

The locations and appearance of demand hotspots change over the time. For example a demand hotspot around an off-street food market only exists during lunch hours and its location depends on the (potentially non-static) location of the food market on the street. This makes deploying an SCBS at the center of the temporary demand hotspot inefficient.

In order to provide good service in cases where SCBS cannot be placed optimally to cover a given demand hotspot, we consider the use of beamforming to increase the signal gain in the direction of the desired demand hotspot. Compared to the use of an Omni-Directional Antenna (ODA) at SCBS, beamforming enables the SCBS to direct its beam to the demand hotspot to overcome the inefficiencies caused by its sub-optimal placement out of the demand hotspot. Ordinarily two options for this are considered: the use of an Active Antenna Array (AAA), or the use of a fixed-beam directional antenna, at the SCBS.

Through independently controlling the phase and amplitude of multiple active antenna elements, AAAs in correlated channels can be used to steer signal gains and nulls in desired directions [2]. This is achieved by directing constructive and destructive interference from the AAA transmissions. As beamforming using AAAs is performed electronically it can be programmed to self-configure and dynamically adjusted to suit the situation. Unfortunately, the use of multiple active elements requires the small cell device to possess multiple transceiver chains, which can dramatically increase the cost and size of the device. Further, the use of AAAs is not always supported for legacy User Equipment (UE) devices, owing to the complex feedback that the beamforming requires.

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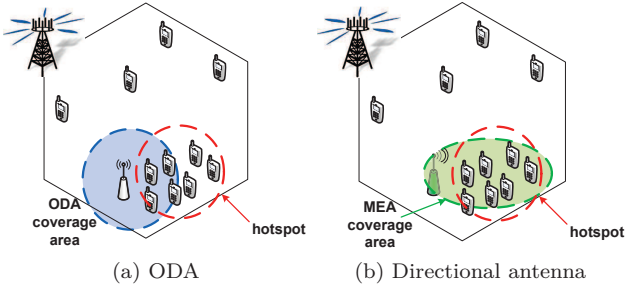


Fig. 1: Small cell coverage with different antennas

Alternatively, fixed-beam directional antennas can be used to provide SCBS beamforming gains in the direction of activity hotspots [3]. One such example is the use of double patch antennas which emit a focused beam. While this presents a more cost effective and legacy UE compatible solution, the direction of the fixed beam must be configured manually at the time of SCBS installation and as such is sensitive to misconfiguration and cannot dynamically adjust its operation to effectively serve demand hotspots. In Figure we show how different the coverage of SCBS would be when it is equipped with an omni-directional antenna and a directional antenna.

Another option, which is the focus of this work, is the use of switched Multi-Element Antennas (MEAs) [4], [5]. In this solution a beamforming gain is obtained in the desired direction by selecting, from multiple differently orientated antenna elements, the one which provides the strongest gain in the demand hotspot direction. As only a single antenna element transmits at each point in time, this solution requires only a single transceiver chain, meaning that it provides a low cost beamforming solution which is capable of self-configuring. Further, by dynamically reselecting the antenna element used for transmission the switched MEAs is also capable of changing its beam direction if the location of the hotspot changes. In [4], the switched MEA system is introduced as a low cost solution for residential femtocells to increase the indoor coverage and reduce the number of mobility events using the mobility-event-based self-optimizing approach [6].

In this paper we use switched MEAs to direct SCBS transmissions toward the desired hotspots. We show that using switched MEAs firstly increases the number of UEs served by the small cell and secondly improves the system performance in terms of total data rate. In this work we also investigate the antenna selection problem and the amount of required samples for confidently selecting an antenna element.

II. SYSTEM MODEL

In this work we consider a scenario in which there are a number of macrocell base stations (BS) covering the considered area and each BS has three sectors. User are randomly distributed in this area; however, there exist some demand hotspots. We deploy small cells to improve the network performance in terms of providing higher data

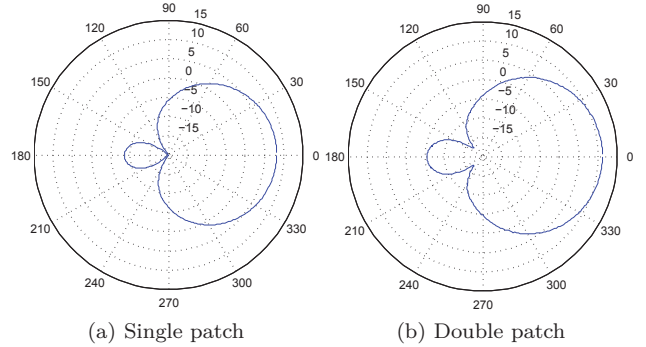


Fig. 2: Antenna pattern

rate for the users. Ideally the SCBSs are deployed at the center the hotspots, but as mentioned, in reality we might not be able to place an SCBS at the center of each demand hotspot. Here, we consider SCBSs that are equipped with switched MEA system (MEA-SCBS).

A switched Multi-element antenna system is a simple solution to benefit from beam directionality. This can be created by equipping the SCBS with multiple antenna elements with distinctive antenna patterns and a switch to select a single or a combination of antenna elements. In this work we consider an MEA with four orthogonal antenna elements. The considered antenna elements are all either single patch or double patch antennas. While the single patch antenna is lighter and smaller in the size, the double patch antenna provides higher antenna gain. The antenna gain pattern of single patch and double patch antennas are shown in Figures 2a and 2b, respectively.

For simplicity we assume that the MEA-SCBSs can activate only one of their antenna elements. The MEA-SCBS selects its best antenna element that captures most of users in the demand hotspot.

III. ANTENNA SELECTION

The best antenna element of any MEA-SCBS can be centrally selected. In this approach the best antenna element is the one that maximizes the system's throughput, which is shown as

$$a^* = \operatorname{argmax} r(a_i), i \in \{1, 2, 3, 4\}, \quad (1)$$

where a^* the best antenna and $r(a_i)$ is the total throughput when i^{th} antenna element is selected at the SCBS. The throughput is computed by the modified Shannon capacity formula [7].

Using the centralized method imposes high computational complexity on the central system and also causes signalling overhead. Distributed decision making is the alternative solution to this problem where each MEA-SCBS selects its best antenna element. Considering that each UE will be served by the SCBS if the received signal power from the SCBS is more than the received signal power from the macrocell base station. The number of UEs that can be served by each antenna element is a metric that can be evaluated based on local information.

Therefore, the MEA-SCBS can select its desired antenna element in a fully distributed manner.

To select the best antenna, the MEA-SCBS in a continuous order turns each of its four elements on and saves the number of UEs that each antenna element serves. The selected antenna can simply be the antenna that serves the most UEs.

$$a^* = \operatorname{argmax}_{s_{UE}(a_i), i \in \{1, 2, 3, 4\}}, \quad (2)$$

where $s_{UE}(a_i)$ gives the number of UEs served by the SCBS when i^{th} antenna is active.

Distribution of UEs in the demand hotspot and the noises in the system can affect the accuracy of selecting the best antenna. Therefore, it is possible that we need to perform the decision iterations multiple times and make the final decision based on the majority rule. We assess the number of decision iterations required based on two definitions of the best antenna: angle-based and T-test-based.

A. Angle-based

In this model we considered the true best antenna element to be the one for which the difference between the angle in which the element is directed and the direction of the hotspot centre-point is smallest. The antenna selection will then be performed based on which antenna element could serve the highest average number of UEs across multiple iterations, between which the UE distribution changed. The number of times that the antenna with the smallest angle has been selected shows how accurate the majority rule is at that specific number of iterations.

B. T-test-based

Since one third of the UEs are contained in the hotspot area, the best antenna element should serve a significantly higher number of UEs than the other antenna elements, regardless of the user distribution. However, cases in which the angle between the center of the hotspot and the antenna direction is close to 45 degrees are more challenging, i.e., two antenna elements might serve a similar number of UEs. Therefore, we use a T-test to realize after how many iterations the selected antenna element significantly outperforms the others.

IV. SIMULATION RESULTS

We consider a standard 3GPP scenario where a tri-sector macrocell is surrounded by 6 other similar cells. We focus on the performance of a single SCBS, attempting to serve a single demand hotspot, where both the SCBS and hotspot are randomly dropped within the coverage region of a selected sector of the central macrocell.

Distributed throughout the macrocell are 30 UEs: two thirds are dropped randomly while one third are concentrated within the demand hotspot. The hotspot is considered to be a circular area with a radius of 10 meters.

The relative locations of the demand hotspot and the SCBS are characterised by γ_{HS} which we define as the

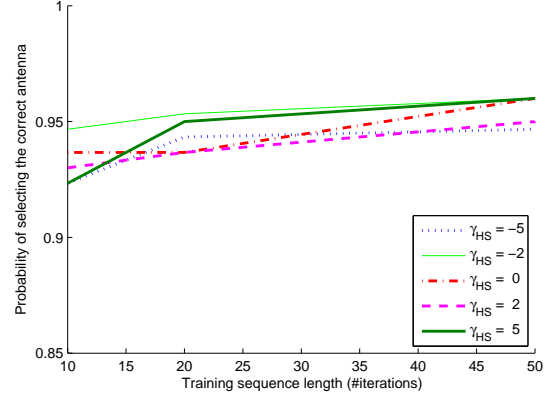


Fig. 3: Best antenna is known: the probability of selecting the best antenna.

received SINR at the centre-point of the hotspot, where the signal source is the SCBS equipped with an ODA and the interference sources are the surrounding macrocells. The macrocell maximum transmit power is 46 dBm and the small cell transmit power is 20 dBm. All base stations have a bandwidth of 10 MHz and 3GPP outdoor scenario pathloss models are applied.

A. Antenna selection training

As mentioned, to select the best antenna the MEA-SCBS turns on each of its antenna elements in turn and checks how many UEs it can serve with each of them. The antenna that can serve the highest average number of UEs after a certain number of such iterations is then selected. In this subsection we investigate the affect of changes in the user distribution at the hotspot on the antenna selection accuracy. In other words the number of rounds that the MEA-SCBS should check all the four antenna elements before making a decision.

Assuming that during the decision period the locations of the SCBS and the hotspot do not change, the worst case scenario that can be considered is that the distributions of UEs within the hotspot and the cell region change each time that the SCBS checks the number of UEs served by each antenna. In this set of simulations we considered 1000 random drops of the hotspot and SCBS locations. For each drop and each decision round we considered a different UE distribution and investigated its effect on the antenna selection.

1) *Angle-based*: Figure 3 shows the relation between the number of rounds over which the antenna selection was averaged (number of times that each antenna element was checked) and the probability of selecting the true best antenna. The figure shows that correct selection of the best antenna is more probable with more samples; however, the increment is quite small, and the probability of selecting the best antenna element with only 10 rounds is over 0.9. We also see that the likelihood of correct antenna selection is not significantly affected by the SINR at the demand hotspot.

ODA SINR at hotspot center	-5	-2	0	2	5
Training sequence length	15.1	16	14.7	15.5	15.2

TABLE I: T-test-based method: required training to confidently select the antenna.

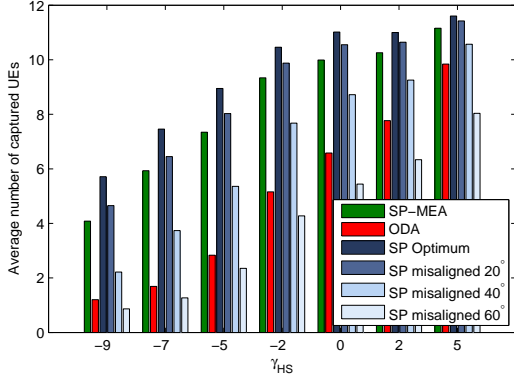


Fig. 4: Average number of served UEs for different antenna configurations. Here a single patch directional antenna is considered for the cases of optimally directed at the hotspot, misaligned by 20°, 40°, and 60°, and the switched MEA case.

2) *T-test-based*: Table I shows the average number of rounds required for the best antenna element to pass the 95% significance T-test. Similar to the previous test we observe that the required number of rounds is almost the same for different SINR values.

Even though, according to the table, on average almost 16 rounds are needed to show that one antenna element significantly outperforms all others, we also found that within *all* simulated iterations, simply selecting the antenna element which served the most UEs (based on a single iteration alone) also provided the same outcome. In other words, for a given SCBS and hotspot placement, the antenna element that served the most UEs remained the same for all user distributions. For this reason, in the remainder of this paper, selection of the best antenna by the MEA-SCBS is performed by comparing the number of UEs served by each antenna element for only a single round.

B. Number of served UEs

In this subsection we compare the performance of the switched MEA-equipped SCBS to ODA-equipped and fixed-direction SCBSs. We compare this in terms of the number of UEs that the SCBS can serve.

For the fixed-direction SCBSs we consider that, as the location of the hotspot may not be accurately known at the installation time, there exists some probability of misalignment. For this reason we consider possible misalignments of 20°, 40° and 60°, as well as the ideal alignment case.

Figure 4 compares the number of served UEs by an SCBS equipped with an ODA, a switched MEA and fixed-direction antenna, where single-patch direction antennas are used. The switched multi-element antenna outperforms the omni-directional antenna which is more significant for

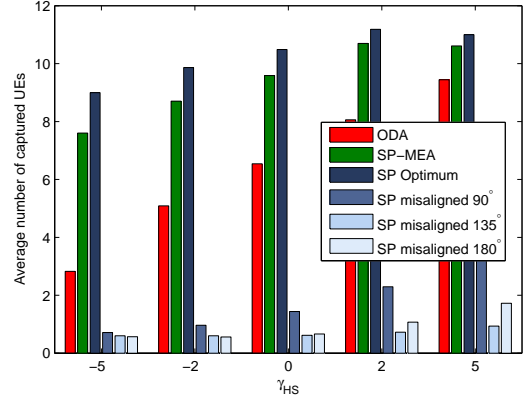


Fig. 5: Average number of served UEs for different antenna configurations when the fixed-directional misalignment is large. Here a single patch directional antenna is considered for the cases where the directed antenna is misaligned with the hotspot direction by 90°, 135°, and 180°, as well as the optimally aligned and switched MEA cases.

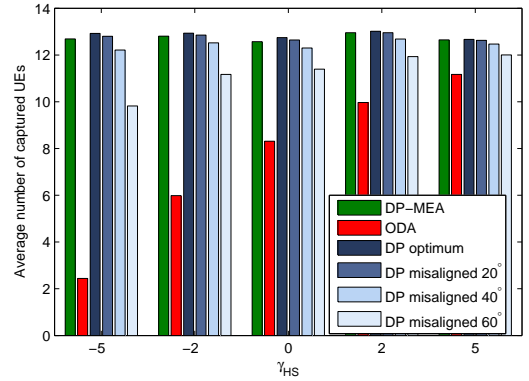


Fig. 6: Average number of served UEs for different antenna configurations. Here a double patch directional antenna is considered for the cases of optimally directed at the hotspot, misaligned by 20°, 40°, and 60°, and the switched MEA case.

lower values of γ_{HS} . The figure also illustrates that the fixed-directional antennas outperform the switched MEA only if the misalignment is less than roughly 25 degrees.

The hotspot location may change in time and therefore there are cases in which the installed directional antenna may end up pointing towards a completely different direction. In Figure 5, we investigated this scenario. The figure clearly shows that in such situations the fixed-directional antennas have poor performance, while the MEA and ODA cases remain unaffected by the major misalignment.

As mentioned previously the antenna gain of the directional antenna can be increased by using two joint antenna patches (double patch) instead of a single antenna patch. The same model can be used in the multi-element antennas and as a result the MEA will have a double-patch antenna in each of its directions which improves its performance. Figure 6 presents the number of UEs that the MEA and directional antennas with different misalignments can serve using double-patch antennas. The figure shows that while the omni-directional antenna's

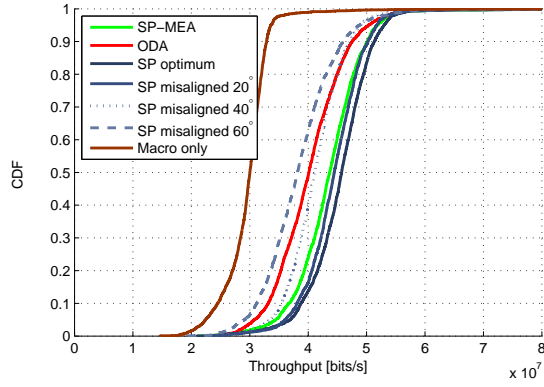


Fig. 7: System performance using different antennas at the SCBS, when the received SINR from the ODA is 0 dB at the center of the hotspot.

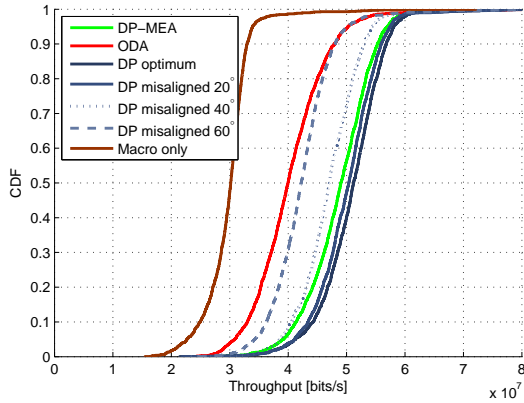


Fig. 8: System performance using different antennas at the SCBS, when the received SINR from the ODA is 0 dB at the center of the hotspot.

performance decreases significantly with γ_{HS} , the double-patch MEA and directional antennas are still capable of covering almost all UEs present within the hotspot area. This figure also illustrates that the effect of misalignment is not as significant in the double patch case as it is for single-patch directional antennas. However, the misalignment is more apparent in lower SINRs.

C. System performance

As the small cell base stations are deployed to assist the macrocell in providing UE higher data rates, we measure the performance of the system in terms of the total data rate. Figure 7 shows the CDF plot of UEs' data rates in the system. The performance of the system without a small cell (macrocell only) is also shown in the figure. The figure clearly shows that using the switched MEA improves the data rate for UEs in the system. The same scenario with the use of double-patch antennas is presented in Figure 8. The figures show that the single-patch MEA and double-patch MEA increase the system rate compared to the omni-directional antenna-based small cell by 10% and 25%, respectively.

V. CONCLUSIONS

In this paper we investigated the performance of switched MEAs as a simple solution to enable the small cells to direct their transmit power. Our simulation results showed that the switched MEA system can accurately train itself and for the training it does not require any additional information. The switched MEA was able to serve more UEs than the omnidirectional antenna and the difference was more significant where the switched MEA had double patch antenna elements. We also show that using switched MEAs instead of omnidirectional antennas can improve the systems data rate up to 25%. It is important to note that unlike the fixed directional antennas the switched MEAs are flexible and they can change their beam direction when the location of the demand hotspot changes.

In our previous work [5] we provided a techno-economical analysis and discussed the cost efficiency of the switched MEA system. Our analysis in this work showed that using multi-element enables the operators to install the SCBS in the locations that are further from the center of the demand hotspot and still achieve the same performance as they used to achieve. This may help the operators to save site rental costs.

To extend our findings in our future works, we will study the interactions among multiple switched MEA-SCBSs. The switched MEA-SCBSs cooperate to improve the systems data rate by avoiding interfering each other. The MEAs can either serve UEs of multiple hotspots or collaboratively serve UEs of a single demand hotspot. We will also study the self-healing mechanisms in such a system.

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